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The 35-day cycle in Her X-1 as observational appearance of freely precessing neutron star and forcedly precessing accretion disk

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Abstract

A careful analysis of X-ray light curves and pulse profiles of Her X-1 obtained over more than 20 years strongly evidences for free precession of a magnetized neutron star with rotational axis inclined to the orbital plane as a central clock underlying the observed 35-day period. Strong asymmetric X-ray illumination of the optical star atmosphere leads to the formation of gaseous streams coming out of the orbital plane and forming a tilted accretion disk around the neutron star. Such a disk precesses due to tidal forces and dynamical action of gaseous streams from the secondary companion. The locking of these torques with neutron star precession makes the net disk precession period to be very close to that of the neutron star free precession.

Introduction

Her X-1 is an accretion-powered 1.24-s X-ray pulsar in a binary system with 1.7-d orbital period [1]. Since its discovery in 1972, this source has puzzled the astronomers by its unusual complex behavior.

The X-ray light curve of Her X-1 is shaped with a 35-day period, consisting of a main-on X-ray state with a mean duration of $\sim$ 7 orbital periods surrounded by two off-states (also called low-on states) each of $\sim$ 4 orbital cycles, and of a a short-on state of smaller intensity with a typical duration of ~ 5 orbits, and is certainly due to periodic obscurations of the X-ray source by the disk. In this system, we luckily observe it under the angle of about 89 degrees, and it is this nearly edge-on position of the line of sight that allows us to study a lot of tiny features in the X-ray light curve. This first of all relates to the so-called X-ray dips, short drops in the observed X-ray intensity accompanied by significant spectral changes, which are observed each orbit after the turn-on. X-ray dips can be explained by different models, but undoubtedly they are produced by occultation of the central source by accreting material.

It is generally accepted that the 35-day period is due to counter-orbital precession motion of a tilted accretion disk around the central neutron star [2, 3]. Even earlier, immediately after the discovery of Her X-1, it has been suggested that free precession of the central neutron star causes the observed long-term modulation with 35-day period [4]. Some evidence for free precession indeed has been obtained from X-ray pulse observed with EXOSAT satellite [5, 6].

The observed stability of the 35-day period over many years would be surprising for purely tidal precession of the accretion disk only, so the need for an underlied clock mechanism was requested. This could be free precession of neutron star, but at that time the locking between the neutron star free precession period and tidal period of the accretion disk was considered as a judicious assumption waiting for its physical grounds.

As was understood already shortly after the beginning of studies of Her X-1, the accretion disk may be twisted. During the counter-orbital precession of such a disk the outer parts of the disk open the central X-ray source while the inner parts of the disk occult the X-ray source [7]. Moreover, a hot rarefied accretion disk corona may exist around its central parts. This makes the ingress to and egress from main-on and short-on states asymmetric. The opening of the X-ray source with a rapid increase of X-ray intensity is accompanied by a notable spectral changes which evidences for the presence of a strong absorption, whereas the decrease in X-ray intensity occurs more slowly and without appreciable spectral changes [8].

One of the intriguing observational facts is that the X-ray source always turns on near orbital phases $\phi_{orb} \simeq 0.2$ or 0.7. Such a behaviour has been explained by [9, 10] by the accretion disk wobbling twice the orbital period due to tidal torques. Indeed, it is at these orbital phases that the disk angle inclination changes most rapidly.

Another notable feature is that the duration of successive 35-day cycles is as a rule 20, 20.5, or 21 orbital cycles [11]. This behaviour has been confirmed by most recent RXTE observations [12].

Even more enigmatic features observed are sudden decreases in X-ray flux (X-ray dips) which are accompanied by significant spectral changes. They have been observed by many X-ray satellites (see [3] for references). X-ray dips are commonly separated into three groups: pre-eclipse dips (P), which are observed in the first several orbits after X-ray turn-on (up to 7 in main-on and up to 5 in short-on states) and march from the eclipse toward earlier orbital phase in successive orbits; anomalous dips (A), which are observed at $\phi_{orb} \sim 0.45 - 0.65$; post-eclipse recoveries (R), which are occasionally observed as a short delay (up to a few hours) of the egress from X-ray eclipse in the first orbit after turn-on.

Changes in the Her X-1 pulse profile with the phase of a 35 day cycle have been found in many observations (see [13, 14] and references therein). As we will show below, to explain such profile variation, emission region on the neutron star surface should have a complex shape: in addition to the canonical magnetic poles, luminous rings around the magnetic poles appear (as first discussed in [15, 16]. Due to free precession, these regions change position with respect to the line of sight producing the observed slow pulse shape evolution with 35-day cycle phase. Rapid pulse profile changes, which are observed at the end of main-on stage, are due to occultation of the neutron star surface by the precessing accretion disk. Soft X-ray sine-like component of the pulse profile remains the only observed in low states, when the neutron star surface is totally screened by the accretion disk. We will show that this component is due to reprocessing of X-ray emission by the innermost parts of the warped twisted accretion disk.

Evidence for free precession of neutron star from X-ray pulse profiles

As is well known, free precession of a non-spherical body changes the angle between a given point on the body's surface and angular momentum vector if none of the axes of inertia coincides with the angular momentum. As a result, magnetic poles, which are the sources of X-ray emission, will migrate with the precession phase, causing modulation of X-ray emission observed by a remote observer.

In the case of free precession of a neutron star with strong magnetic field surrounded by a diamagnetic thin accretion disk, the magnetospheric torques applied to the disk will also change with the precession phase (see [17] and references therein). The same torque but with the opposite sign will be applied from the disk to the neutron star through the magnetic field. The value and sign of this torque, averaged over the rapid neutron star rotation, are both dependent on the obliquity angle θ between the angular momentum

Figure 1: *Ginga* X-ray pulse profiles from paper [14]

and the magnetic pole. There is a critical value of this angle, $\theta_c = 54^o44''$, at which the average torque vanishes and the innermost parts of the disk remain unperturbed. If $\theta > \theta_c$, the inner disk acquires a twisted (helical) shape. The disk tends to keep in the equatorial plane of the rotating neutron star. If $\theta < \theta_c$, the disk also tends to keep with the neutron star equator, but with opposite helicity.

The disk-magnetospheric interaction is a very complex and ill-understood, and in the case of neutron star free precession it seems likely that the rotational axis of the neutron star keeps oblique with respect to the orbital plane. The initial orbital inclination of the neutron star axis can be caused by asymmetric supernova kick. However, accreted matter from the disk brings angular momentum which secularily tends to align the neutron star rotational axis with the orbital one. During free precession it is possible to incline the neutron star rotation axis by magnetospheric torques. Due to the helicity of the inner accretion disk (disk is not planar!), the neutron star spin axis tends to lie into the orbital plane at $\theta < \theta_{cr}$ and vice versa. The resulting inclination angle depends on the sum of differentials $\Delta\theta$ caused by both magnetospheric torques and angular momentum of accreted matter braught to the neutron star over precession cycle.

In the simplest case of emission from magnetic poles only, the pulse profile would consist of one or two pulses, depending on the visibility conditions of the poles by the observer. However, in Her X-1 the pulse profile has a more complicated shape (see Fig. 1). It consists of several peaks that change first slowly and then rapidly with the precession phase. To explain such an evolution, one needs to introduce a ring-like structures around magnetic poles (for example, during a complex magnetic field structure near the neutron star surface, [15]. Such ring-like structures may be a natural result of a slow creeping away of amorphous, well-conducting matter stored near the poles in the course of accretion of plasma. During this process, the magnetic field diffuses through the matter due to Ohmic dissipation of currents, so one may simultaneously have several such structures of different sized around the pole, and they well may have an elliptical, off-center shape around the poles. The glowing of such rings is due to separation of the accreting flow above the neutron star surface into different flows. In fact, these rings can be describe as additional magnetic moments of the opposite sign relative to the main magnetic moment of the neutron star [15]. As a result, at a distance of several radii above the magnetic poles, the zone appears with practically zero net magnetic field. It is in these zones where the accretion flux separation occurs. Clearly, the most pronounced emission will be from the rings most close to the poles, and the analysis of pulse profiles of Her X-1 shows that there is two such rings around each pole.

In the main-on state of Her X-1 ($\phi_{pr} = 0 \div 0.24$) the magnetic poles and the rings lie closer to the rotational axis, and in the short-on state ($\phi_{pr} = 0.5 \div 0.7$) they are closer to the rotational equator, and moreover cross it during the precessional motion (cf. relative intensity of the poles at phases 0.6-0.7 and in Fig. 1).

Only a sine-like shape of the X-ray pulse remains visible starting from $\phi_{pr} \approx 0.26$ in the end of main-on state, and at $\phi_{pr} \approx 0.66$ in the end of low-on state [13]. Notably, these sine-like components are phase-shifted by 180 degrees, which is a natural consequence of precessional turn of the warped parts of inner accretion disk.

ASM RXTE analysis of 35-day light curve

All-Sky Monitor onboard RXTE satellite [18] has obtained a lot of data on Her X-1. The data archive contains X-ray (2-12 keV) count rates averaged over predominantly 90-s time intervals started from MJD 50087. This monitoring revealed that the 35-day modulation stopped at the end of March of 1999, the source entered into an anomalous low state which continues at present. Before this anomalous state, 32 full 35-day cycles were continuously observed (Fig. 2). Below we present the updated analysis of these data (see [12] for early study).

Despite some gaps in the data, the archive is especially useful in reconstructing the mean X-ray light curve by means of superposing many cycles with account of turn-on times phases. In addition, it is possible to determine the turn-on times of 35-day cycle with a good accuracy. This accuracy is limited by the RXTE observations (the maximum UHURU count rate from Her X-1 was about 100 counts per second while that of RXTE is about ≤ 10 counts per second), nevertheless one may clearly distinguish around which orbital phase, 0.25 or 0.75, each cycle was turned-on.

The analysis reveals that 19 cycles turned on near binary phase 0.25, and 13 near phase 0.75 (see [19] for more detail and description of method used). The folded light curves for 0.25 and 0.75 cycles, as well as the mean 35-day light curve are presented in Fig. 3. Qualitatively, both main-on and short-on stages are seen. During the main-on stage, the source reaches the peak count rate in 1.5 orbits, stays at maximum for ~ 2 orbits, and progressively fades to minimum during 3.5 orbits. The beginning of the short-on stage is separated by 4.5 orbits from the end of the main-on. The duration of the short-on state is about 4.5 orbits.

Note that the form of the short-on stage is similar to that of the main-on: a rapid

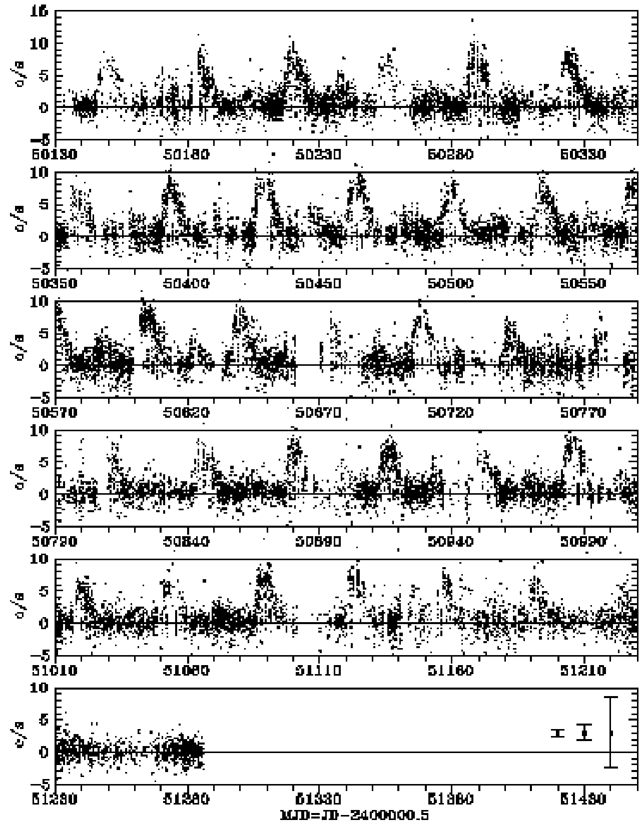

Figure 2: ASM RXTE data

increase and slow decrease of count rate. The main-on state is separated by the similar 4.5 orbits' off-state from the end of the short-on state. The short-on stage decreases more slowly than the main-on, so it is difficult to say where the second off-state really starts. A weak X-ray glow persistent during off-states is possibly due to scattering in the accretion disk corona.

The anomalous dip is clearly seen for 0.25 cycles during the first orbit after the main turn-on and is practically invisible at 0.75 cycles. For both types of cycles, pre-eclipsing dips demonstrate identical behaviour – they march from the eclipse toward earlier orbital phase in successive orbits. No post-eclipse recovery was found in the main-on state for 0.75 cycles.

Origin of X-ray dips

In our model, a tilted twisted counter-orbitally precessing accretion disk eclipses the central X-ray source between the main-on and short-on states. We model the disk by

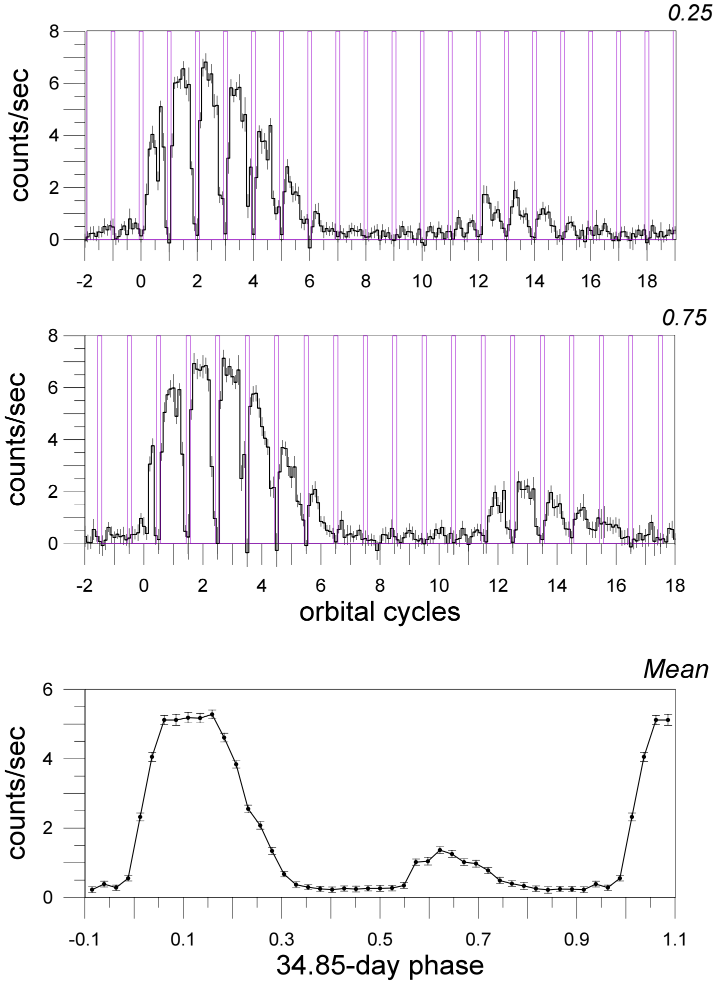

Figure 3: Mean X-ray light curves of Her X-1: for 0.25 cycles (upper panel), 0.75 cycles (middle panel), and for all RXTE cycles (without eclipses).

three parts: the outer disk, which is inclined by an angle of $\sim 5^o$ relative to the orbital plane, the intermediate disk with approximately the same inclination as the outer disk but turned counter orbital rotation by an angle of 80 degrees, and the innermost disk whose orientation and inclination are determined by magnetospheric torques. The disk ends at about the corotation radius $R_c = (GM/\omega^2)^{1/3}$, where $\omega = 2\pi/P$ is the neutron star angular rotation frequency and M its mass. The outer and intermediate disks counter precess as a solid body, while the innermost disk changes orientation: in the main-on its inclination is about 9 degrees with a helicity angle of $\sim$ 9 degrees with respect to the intermediate disk, and in the short on the helicity is opposite with the same angle -9 degrees. Such variations are caused by changes in the angle θ between the neutron star

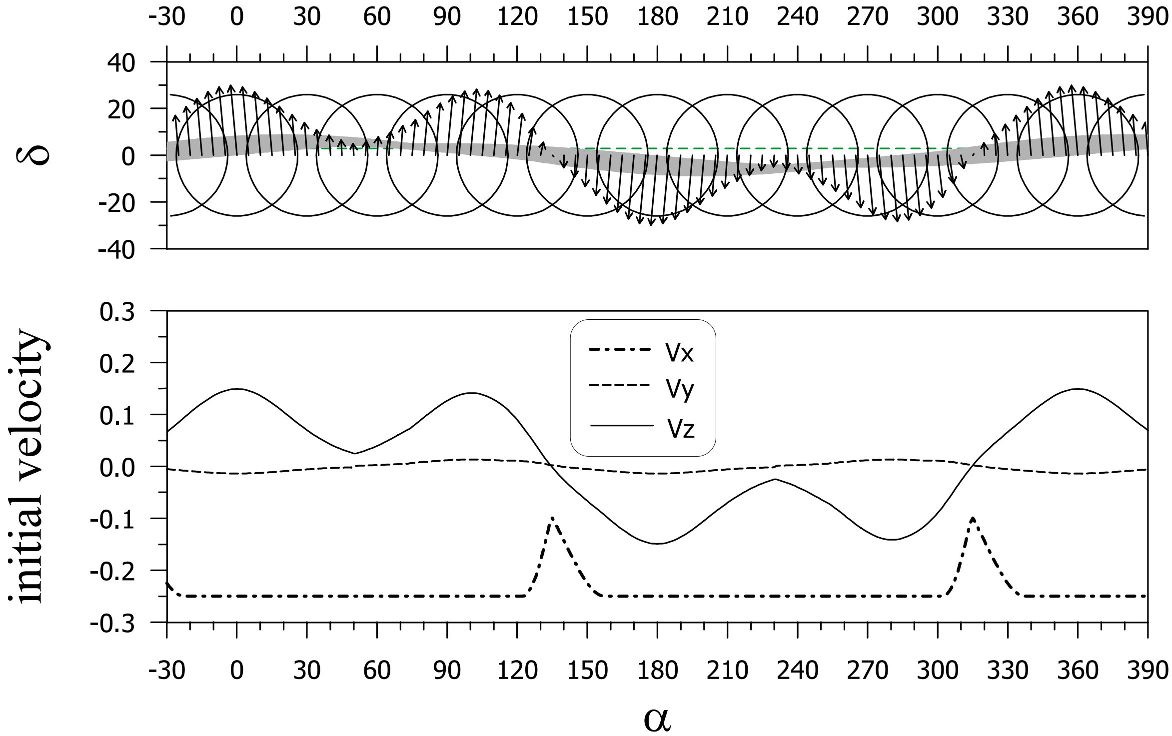

Figure 4: Upper panel: the passage of HZ Her through the shadow formed by a tilted twisted accretion disk. The coordinates α and δ count from the line of nodes of the middle part of the disk along the orbital motion and from the orbital plane, respectively. The dashed line indicates the position of an observer inclined by $i = 89^o$ to the orbit. The arrows show the projection of the initial accretion stream velocity on the plane YZ perpendicular to the orbit. Bottom panel: The initial stream velocity components at the L_1 point in units of the relative orbital velocity 270 km/s.

angular momentum and magnetic dipole axis. At $\theta = \theta_{cr}$ magnetospheric torques vanish and the innermost disk coincides with the intermediate one. This takes place somewhere at low-on states (where the neutron star surface is screened by the disk), when the magnetic pole goes up and down in due course of precession.

Such a disk produces an appreciable shadow and the optical star periodically enters this shadow in its orbital motion (Fig. 4). The shadowed region is such that not all the optical star surface is screened by the disk – there always should exist areas illuminated by the X-ray source with a photospheric temperature of 15,000-20,000 K whereas photospheric temperature of the unheated regions is as low as $\sim 8,400$ K. Even higher temperatures (up to 10^6 K) due to soft X-ray absorption by heavy elements are attainable in the chromospheric layers over the photosphere.

Such a high temperature induces matter outflow from the optical star which would lie in the orbital plane in the absence of the shadow. When the shadow appears, a powerful pressure gradients emerge in the chromospheric layers near the boundary separating illuminated and obscured parts of the optical star, which initiates large-scale motions of matter near the inner Lagrangian point L_1 with a large velocity component perpendicular to the orbital plane [20, 21]. Such a shadow will periodically modulate the matter outflow rate $\dot{M}$, which is dramatically reduced when the L_1 point is deep inside the shadow, and rises rapidly to a maximum at the moment when the shadow edge intersects the L_1 point. Clearly, the picture repeats twice over the synodal orbital period.

Thus, matter flows non-coplanar with the orbital plane emerge and supply the accretion disk with angular momentum non-parallel to the orbital one. Depending on the initial velocities, these streams may even increase the disk tilt to the orbit. Such streams coming out of the L_1 point intersect the line of sight of the observer at some orbital phases shortly before the X-ray eclipse and shift slowly toward earlier phases as the precession progresses. This is exactly the behaviour of the pre-eclipse X-ray dips observed. The streams intersect the line of sight at other orbital phases as well and thus give rise to the type I anomalous dips.

The problem of matter outflow from an asymmetrically illuminated stellar atmosphere is essentially three-dimensional and requires sophisticated numerical calculations. To obtain the pre-eclipse dips in a simplified model, we calculated non-planar ballistic trajectories of particles ejected from the point L_1. Some trial functions for the initial outflow velocity components are used (see [19] fro more detail).

Before colliding with the disk, non-planar streams intersect the line connecting the observer and central X-ray source thus absorbing some X-ray flux. We identify these events with the pre-eclipse and type I anomalous dips. In Fig. 5 we plot the calculated and observed dip positions on the $\phi_{orb} - \phi_{pr}$ plane. The contours include the calculated dip positions for different minimal distances between the stream centre and the line of sight (0.02, 0.04, 0.06 and 0.08). The stream generated when the star again enters the X-ray illuminated sector must also intersect the line of sight during the short-on state $\phi_{pr} = 0.35 - 0.65$. This gives rise to the pre-eclipse dips during the short-on state as well, as indeed observed [22, 23, 12].

Fig. 5 demonstrates qualitative agreement between the observed and calculated dip positions. Note that in our model additional pre-eclipse X-ray dips can appear at the end of the main-on and short-on states. By varying slightly the parameters it is easy to obtain the merging of the end of the pre-eclipse dip with the beginning of such "third" dips, so that the central X-ray source remains unobservable until the beginning of orbital

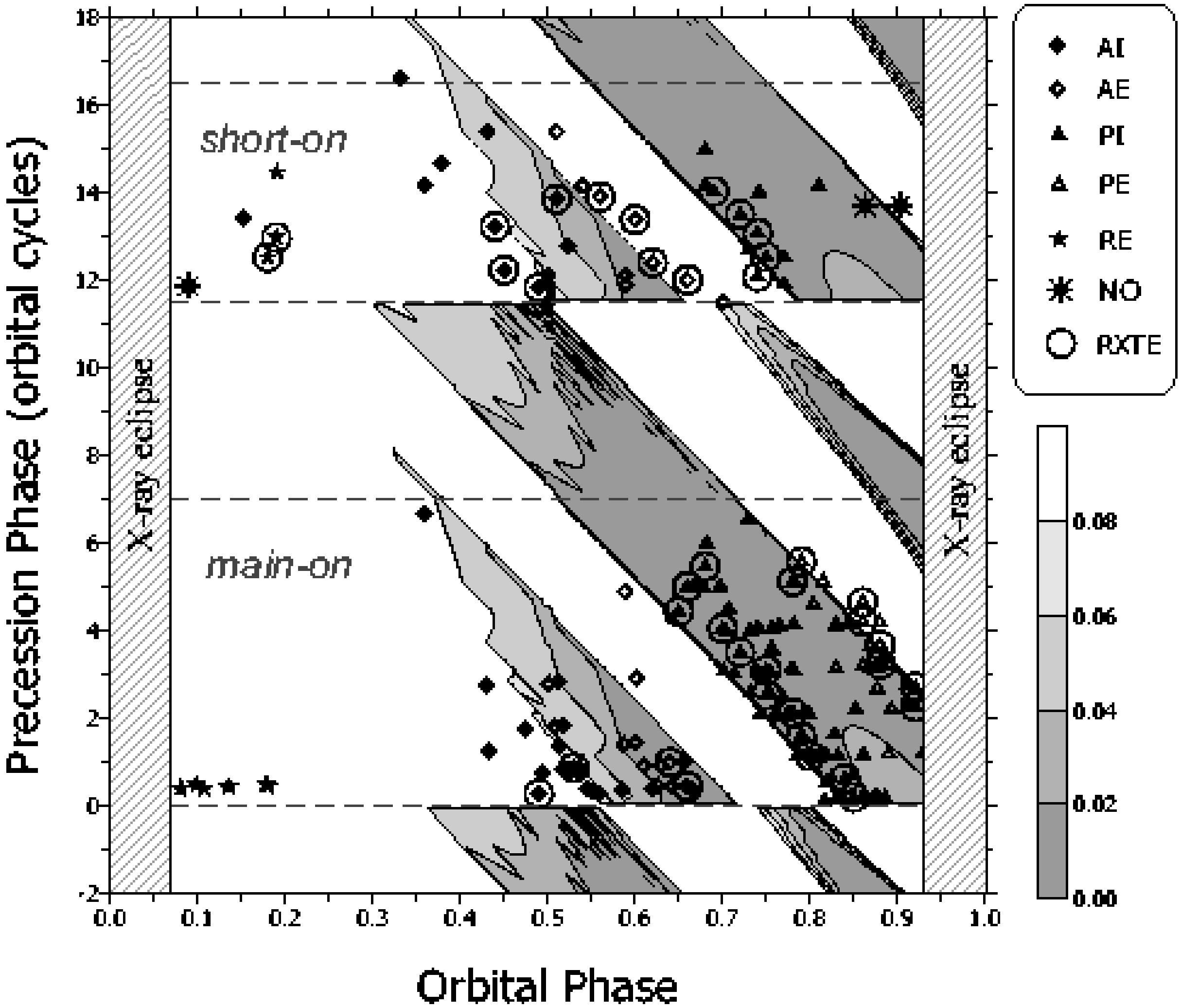

Figure 5: The part of the plane $\phi_{orb} - \phi_{prec}$ with the observed pre-eclipse and anomalous X-ray dips in the main-on and short-on states. Quadrangles and triangles indicate ingress to (PI) and egress from (PE) the pre-eclipse dips. RXTE data are encircled. The calculated pre-eclipse dips and short anomalous dips arise when the accretion stream intersects the line between the X-ray source and the observer before entering the disk. Different contours correspond to different minimal distances (0.02, 0.04, 0.06, 0.08) between the stream centre and the line of sight.

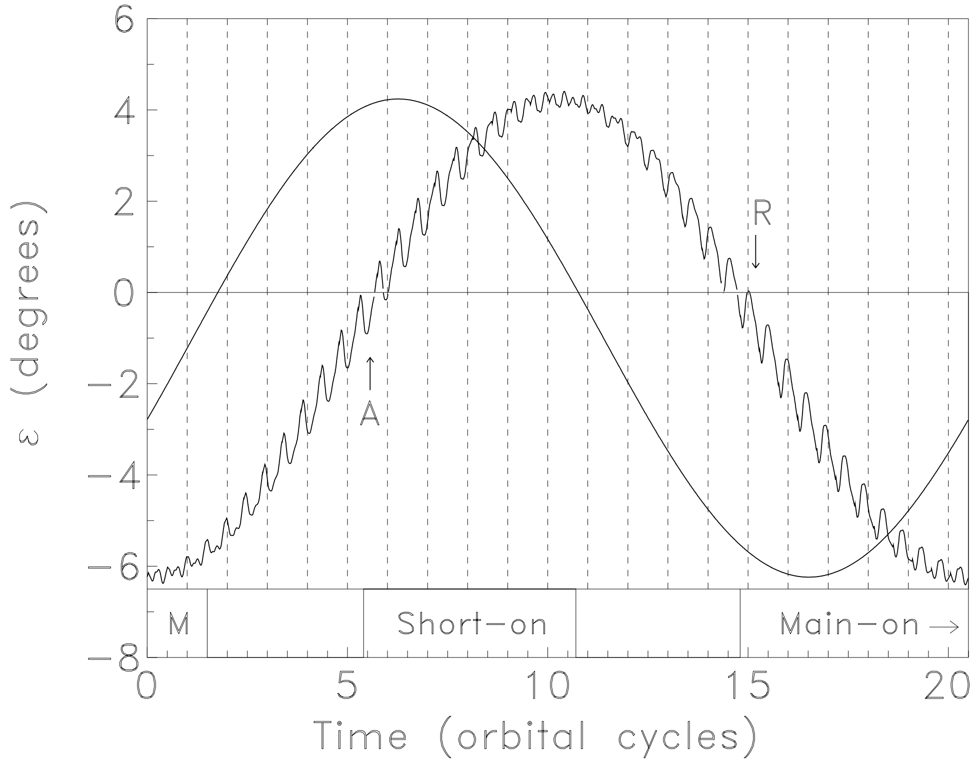

Figure 6: Angle ϵ between the line of sight and the outer accretion disk plane (the jagged line) and intermediate disk plane (the smooth line) as a function of time (in orbital cycles). Small veridical arrows indicate anomalous X-ray dips of type II (A) and post-eclipse recovery (R).

X-ray eclipse. Indeed, *Ariel-V* data [23] clearly demonstrated the absence of egress from pre-eclipse dips at several short-on states!

Unlike the pre-eclipse dips and type I anomalous dips, the anomalous dips of type II and post-eclipse recoveries are formed by another mechanism. The vector of the outer disk angular momentum moves along a precession cone and undergoes an oscillating (wobbling) motion twice the synodical orbital period. The wobbling arises due to joint action of streams and tides (see Fig. 6 and [3] for more detail). The wobbling amplitude is higher in short-on than in main-on state, which can be a possible reason for more strong appearance of post-eclipse recoveries observed in short-on.

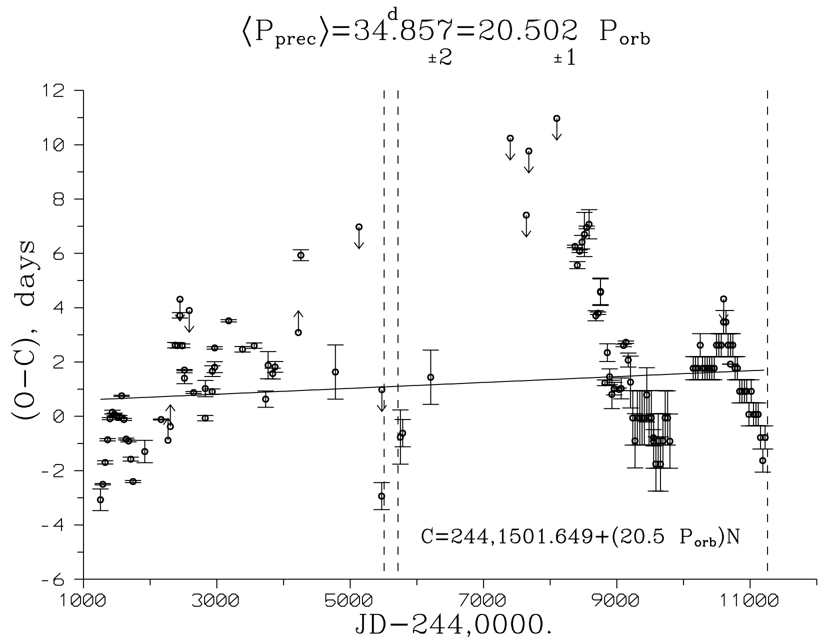

Figure 7: Observed minus Calculated (O-C) diagram for turn-ons of Her X-1 over 28 years. The dashed curves indicate 9-months' anomalous low state of Her X-1 in 1983-84, and the beginning of the current anomalous low state (March 1999).

Discussion and conclusion

The model of the unique binary system Her X-1 invokes both a free precessing neutron star and a tidally precessing accretion disk. Clearly, in general case the neutron star free precession period and accretion disk precession period should be different. In Her X-1, X-ray source opens by the precessing outer parts of the disk. As we noted above, the turn-ons always occur randomly in 20, 20.5, or 21 orbits. The result of this random process is that time delay in some turn-ons relative to the mean ephemeris can be as long as 3-3.5 orbits (see Fig. 7). Nevertheless, the mean period is $\langle P_{prec} \rangle = 34^d.875 \pm 0^d.002 = 20.502 \pm 1 \times P_{orb}$, which we believe to be the neutron star free precession period. The closeness of this period to 20.5 orbits is quite spurious (cf. the closeness of apparent angular diameters of Sun and Moon). Actually, this period is not the strict one, since the neutron star can undergo quakes etc. We believe that the locking of the disk precession with the neutron star free precession is due to dynamical action of the gaseous stream forming the disk: when it tends to go ahead, the streams brake its precessional motion, and vice versa.

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